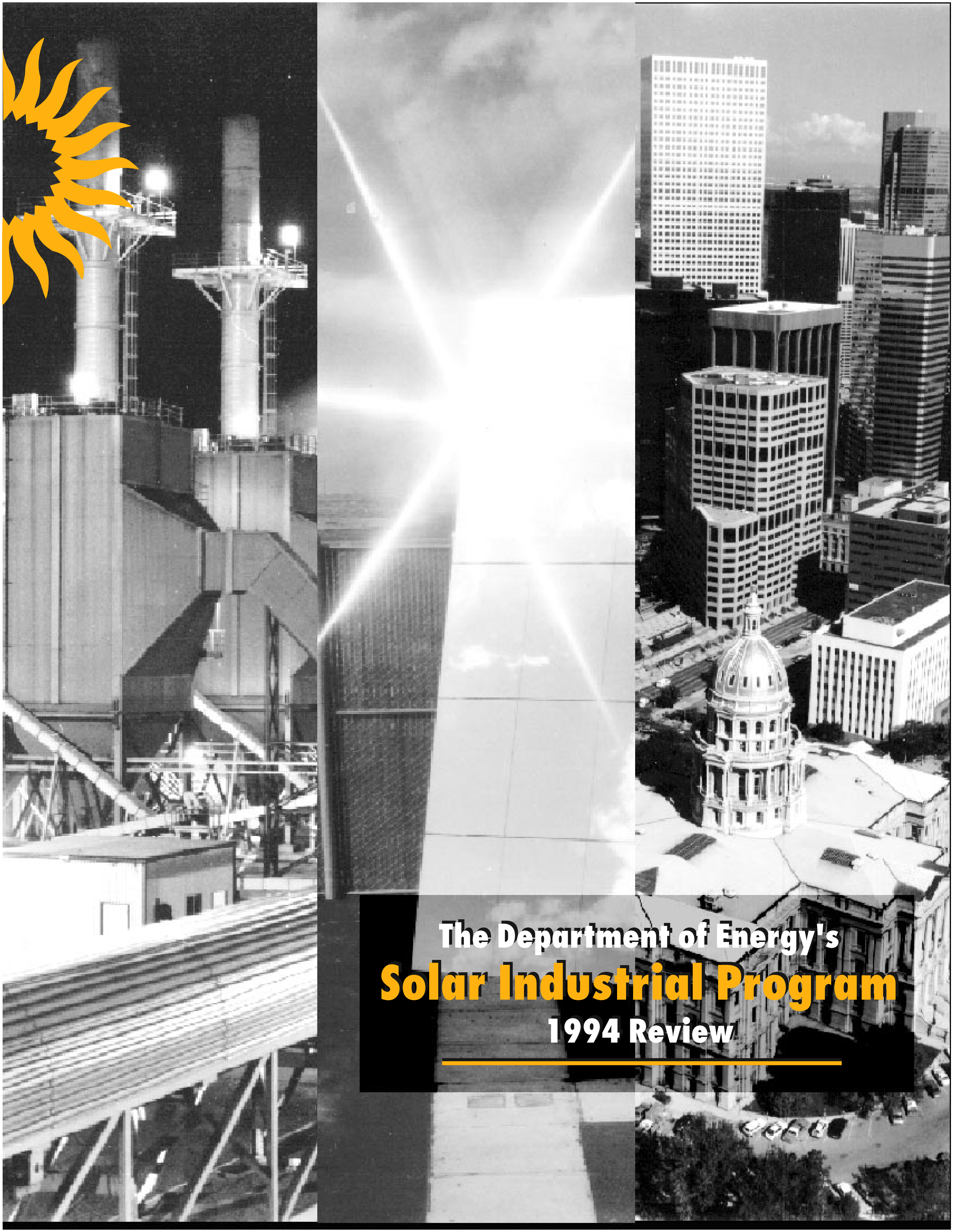


The Department of Energy's Solar Industrial Program

1994 Review

The Solar Industrial Program: Bringing Solar Solutions to American Industry


The sun-tracking heliostat at the High-Flux Solar Furnace in Golden, Colorado.

For the Department of Energy's (DOE's) Solar Industrial (SI) Program, 1994 was a year characterized by momentum—momentum toward increasing the amount of solar-derived energy used by American industry. Building on a foundation of successful research, development, and demonstration projects laid during the last decade, the SI Program entered into an unprecedented number of joint projects with private companies and government agencies in 1994.

The DOE's SI Program supports research, development, and demonstration of solar technologies specifically for American industry. Two pressing issues drive the SI Program's work: industry's need for stable sources of inexpensive energy and society's growing concern about the environmental consequences of relying on fossil fuels for power.

During 1994, the SI Program aggressively addressed these issues through laboratory research and industrial partnerships. By working directly with diverse industrial partners—from electronics manufacturers to waste management firms—the SI Program is moving solar technologies out of the laboratory and into commercial use.


SI Program researcher monitors solar detoxification field test at a superfund site in California.

An Extensive Resource Base

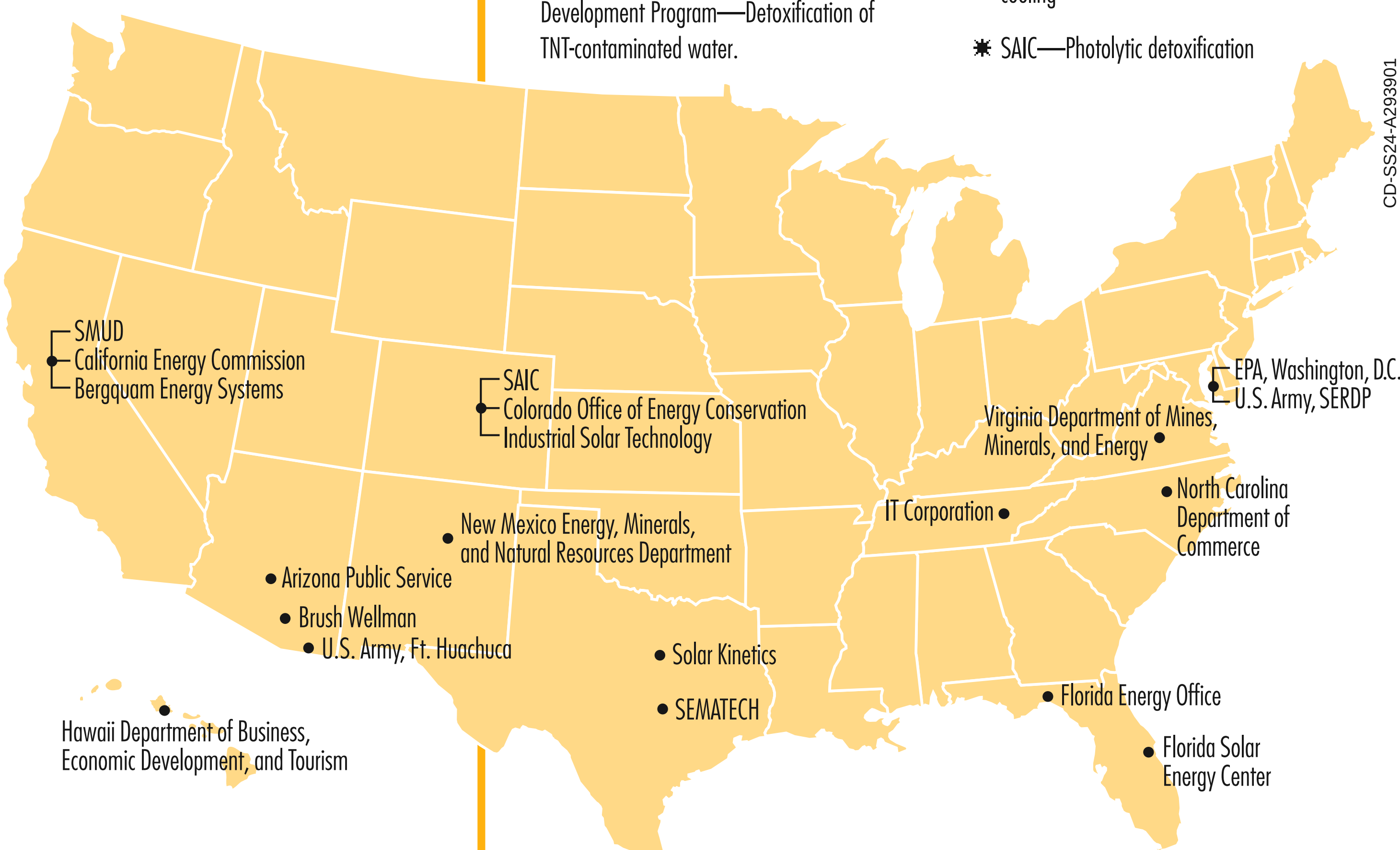
The Solar Industrial (SI) Program is managed within the Department of Energy's Office of Industrial Technologies. The SI Program works with numerous other government agencies, including the Environmental Protection Agency and the Department of Defense in researching and developing industrial-scale solar technologies.

The National Renewable Energy Laboratory (NREL) in Golden, Colorado, manages the SI Program. Technical work is carried out at NREL and Sandia National Laboratories.

Program Partners

During 1994, the Solar Industrial Program worked directly with American industry through a number of formal mechanisms, such as cost-shared subcontracts and cooperative research and development agreements. The following is a small sample of our partners and the work we are jointly pursuing:

- IT Corporation—Gas-phase detoxification
- SEMATECH—Detoxification in the semiconductor industry
- Brush Wellman—Metallized ceramic manufacturing
- The States of California, Colorado, Florida, Hawaii, Virginia—Solar heat for state facilities
- U.S. Army—Solar-powered air conditioning at Ft. Huachuca, Arizona
- U.S. Army, Strategic Environmental Research Development Program—Detoxification of TNT-contaminated water.
- The Sacramento Municipal Utility District, the City of Tallahassee Electrical Department, and the Arizona Public Service Company—Solar heat for demand-side management
- U.S. Bureau of Mines—advanced manufacturing
- Bergquam Energy Systems—Solar water heating and cooling
- Solar Kinetics, Inc.—Aqueous-phase detoxification
- Florida Solar Energy Center—Solar heating and cooling
- SAIC—Photolytic detoxification



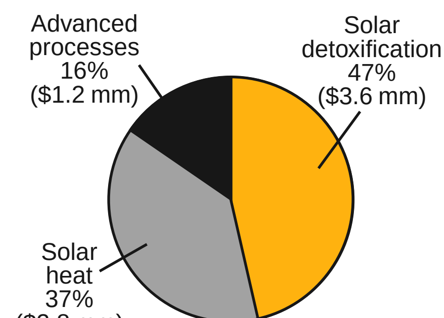
On-going laboratory development is a crucial part of the SI Program's detoxification research.

The concept of government-industry *partnership* is crucial; these partnerships bring together complementary resources and expertise. Industry brings expertise in specific industrial processes and markets, and the SI Program brings the vast resources available within the DOE's network of national laboratories. Often, the two parties share the research and development costs, thereby leveraging industry's R&D dollars. Ultimately, these collaborations improveeconomic competitiveness, create jobs, and advance our understanding of solar technology.

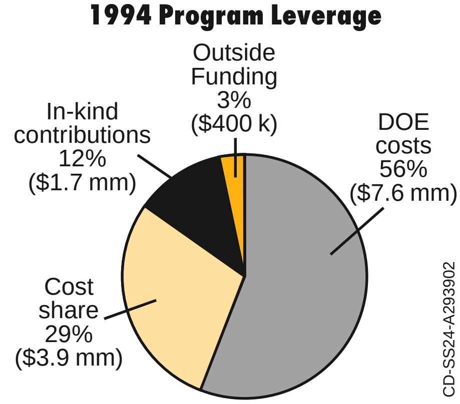
The Solar Industrial Program in 1994

In 1994, the SI Program joined together with industry giants such as SEMATECH, International Technology (IT) Corporation, and Texas Instruments to develop solar processes for a variety of applications, including destroying organic contaminants in exhaust air produced during the manufacture of integrated circuits, manufacturing metallized-ceramic electronic components, and surface treating high-wear mining equipment. Collectively, our industry partners expended $6.0 million on these projects, while the SI Program funded $7.6 million of the cost-shared research. The graphs at right show the breakdown of the SI Program's budget in 1994.

1994 Solar Industrial Program Budget
Total: $7.6 mm



1994 Program Leverage



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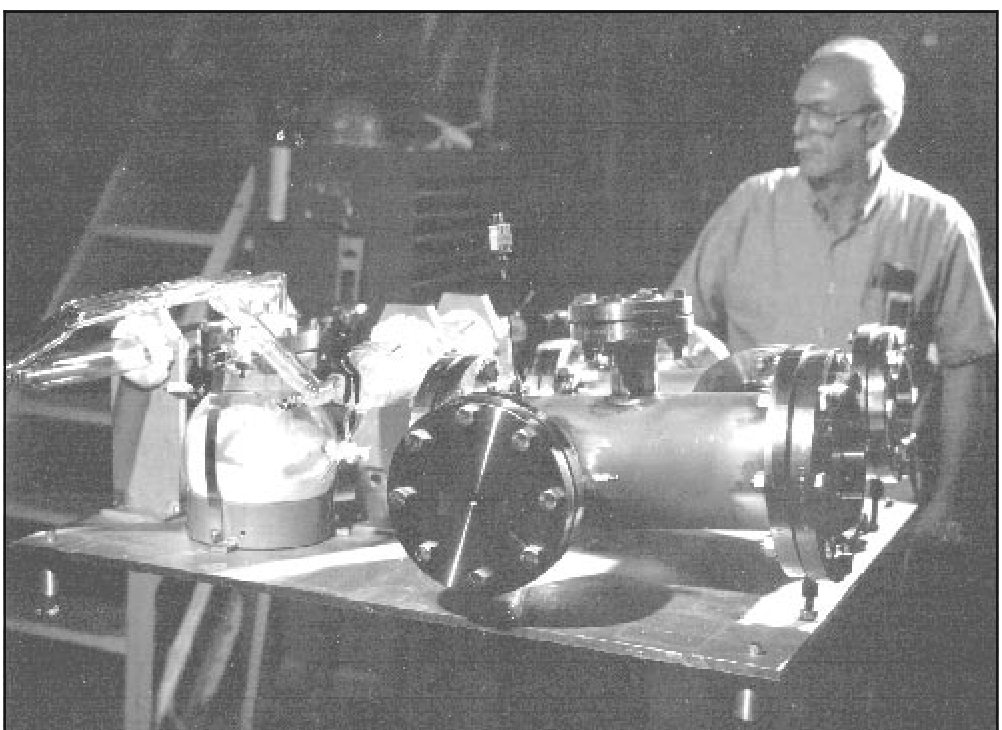


Program researcher prepares an experimental high-temperature reactor for on-sun testing.

The SI Program is divided into three subprograms:

- Solar Detoxification—using solar energy to destroy environmental contaminants in air, water, and soil.
- Solar Process Heat—generating industrial quantities of hot water, steam, and hot air from solar energy.
- Advanced Processes—using concentrated solar energy to manufacture high-technology materials and develop new industrial processes.

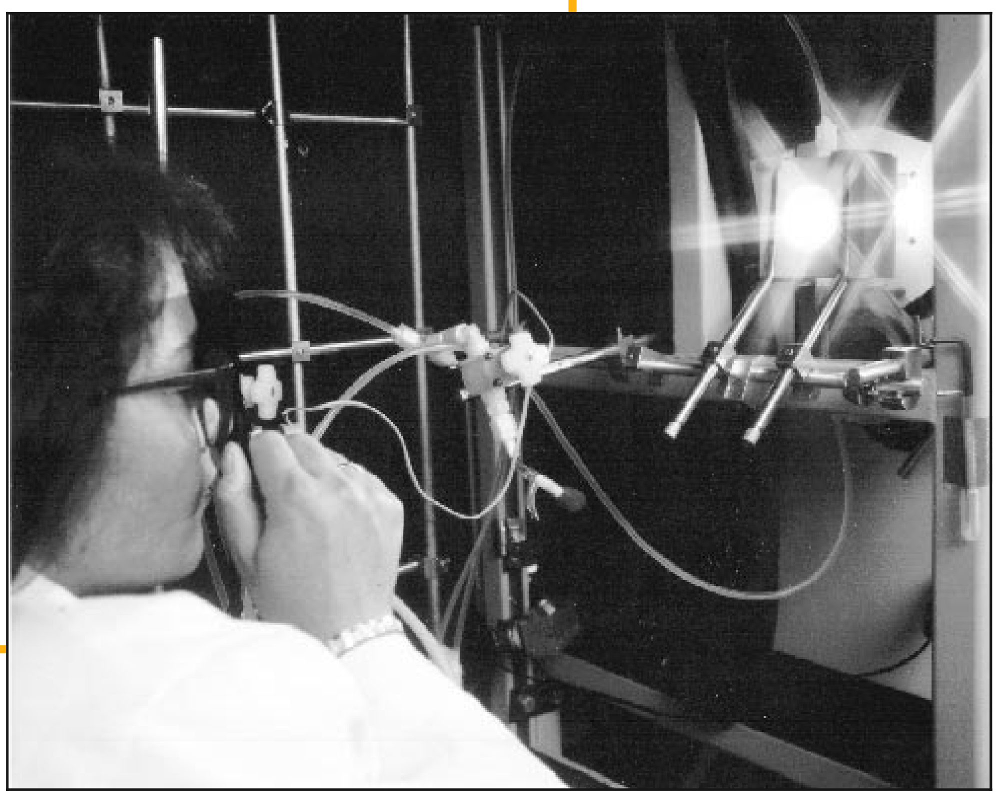
The specific accomplishments that occurred in each of these three areas in 1994 are discussed in the pages that follow. The direction each of these technologies is heading in 1995 and beyond is also presented, as are the specific challenges each faces in the quest to achieve wide-scale commercial use.

Success Begins in the Lab

Successful technology development begins with painstaking, fundamental scientific investigations—the kind of work researchers within the DOE's national laboratories conduct throughout the technology development process.

Scientific research is an important part of the SI Program. For example, researchers continue to improve the solar detoxification process through catalyst research and process chemical engineering studies. The Program's work in advanced processes is based almost exclusively on laboratory-scale investigations into the nature of highly concentrated solar radiation—a largely unexplored discipline with enormous scientific and engineering potential. Often, laboratory results lead researchers in new directions, giving rise to new technologies and areas of inquest.

The DOE's ability to conduct solar energy research is unequaled, and this research is the foundation on which the eventual commercial success of the technology is built.



Solar Detoxification

Solar detoxification technologies use the energy in sunlight to destroy environmental contaminants. These technologies have joined the fight against organic and inorganic pollutants—such as degreasing solvents and spilled fuel—at contaminated sites across the United States; they also bring industrial processes into compliance with Environmental Protection Agency regulations under the Clean Air Act, Clean Water Act, RCRA, and Superfund. And the technology is versatile; all types of polluted media (air, water, and soil) are being treated with solar detoxification.

One of the detox techniques—photocatalytic oxidation (PCO)—uses an inert chemical compound that becomes highly reactive in the presence of ultraviolet sunlight. When polluted air or water is exposed to this activated catalyst, the bonds holding together the polluting molecules are broken, converting the toxins into water, carbon dioxide, and other benign compounds.

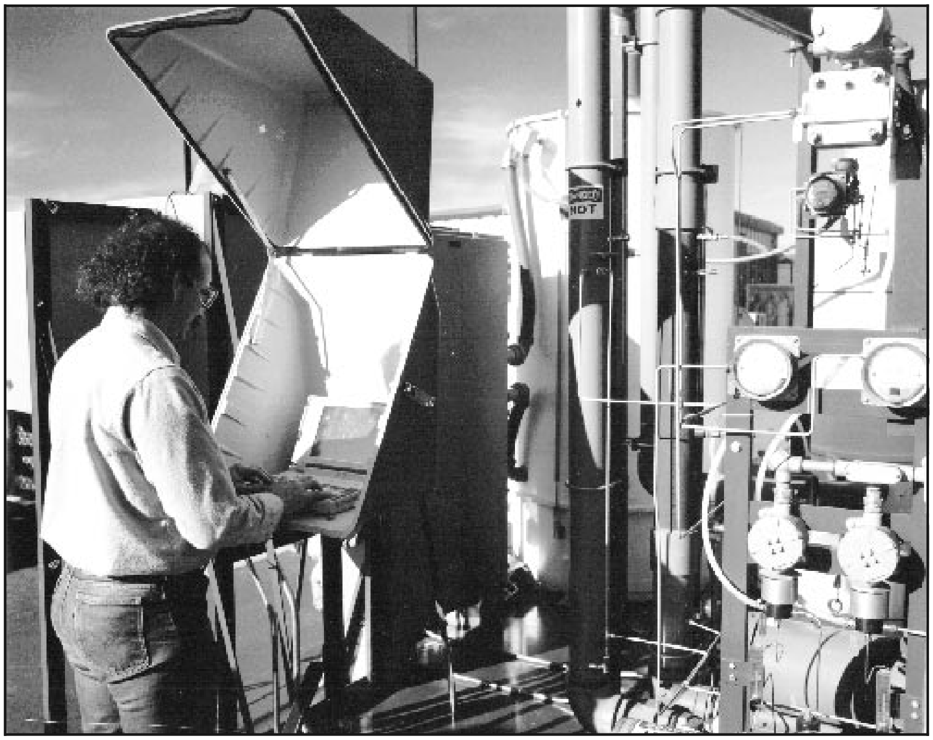
The other detox technique—photolytic detoxification—relies solely on concentrated sunlight to destroy contaminants. The technique uses precisely aligned mirrors to concentrate solar energy similar to the way a magnifying glass concentrates sunlight when held at just the right angle. These detoxification systems concentrate the sun to 1000 times its normal intensity at the surface of the earth. Environmental contaminants exposed to this intense solar energy rapidly oxidize into simple, harmless molecules.

The Solar Industrial Program has been researching detoxification technologies since 1988. The initial laboratory work determined basic process characteristics, catalyst performance, and optimal system design. Field testing began in 1991 and resulted in the technology receiving a prestigious R&D 100 Award. Although the technology is now being demonstrated at numerous industrial sites, SI Program researchers continue laboratory R&D to improve performance and reduce system costs.

Solar Detoxification in 1994

In 1994, the Solar Industrial Program took great strides helping our industrial partners bring solar detox into commercial use. The collaborative detox research and development projects initiated with industry were the key to this success. Major industrial firms, environmental companies, chemical companies, and solar equipment manufacturers all signed on to take part in detox R&D, testifying to the confidence the private sector has in the near-term commercial success of this technology.

IT Corporation, one of the nation's largest environmental technology firms, signed a cooperative research and development agreement (CRADA) with the SI Program



(Above) IT Corporation's pilot-scale detoxification system. Researchers use this portable unit at waste sites to determine if detoxification technologies can be successfully applied given the site-specific conditions. (Right) A laboratory-scale version of IT's gas-phase detoxification reactor. SI program researchers continue to improve process performance in the laboratory. The TiO2 catalyst suspended in the reactor vessel can be activated by either sunlight or electric ultraviolet light.

early in the year to develop a gas-phase photocatalytic oxidation reactor. Under this 2-year agreement, the two partners will design and build a pilot-scale reactor. During 1994, SI Program researchers improved IT's reactor vessel design, boosting the contaminant-destruction efficiency of the unit from 30% to more than 90%. The project will culminate with IT demonstrating this system at an industrial site in 1995.

SEMATECH, the research consortium of the nation's leading semiconductor manufacturers, also signed a CRADA with the SI Program to develop the photocatalytic oxidation process. SEMATECH is interested in using detox systems to treat contaminant-containing air streams produced during the manufacture of semiconductors. SEMATECH is identifying specific contaminants to be treated, and SI Program researchers are determining if detox technology can effectively treat individual contaminants and streams containing multiple contaminants. In late 1994, SI Program researchers built a laboratory system, which incorporates an infrared spectrometer for detecting previously undetectable compounds, specifically for this work. The SI Program and SEMATECH will test a detoxification system at a semiconductor manufacturing facility in the summer of 1995. If the test is successful, IT Corporation will be in a position to market the technology to the semiconductor industry.

Solar Kinetics, Incorporated (SKI), and the SI program entered into a cost-shared partnership to demonstrate the detox process on contaminated water. SKI, a solar equipment manufacturer, has selected a contaminated groundwater site at Kelly Air Force Base in San Antonio, Texas, to construct and operate this demonstration system. Researchers from the SI Program are assisting SKI with technical and design issues. The system is scheduled to begin operating in 1995.

The SI Program is working with SEMATECH, the R&D consortium of computer chip manufacturers, to determine if detoxification technology can be applied to waste streams produced during the fabrication of semiconductors.

The SI Program continued to work with SAIC, the U.S. Army Environmental Center, and the Environmental Protection Agency to design, build, and operate a photolytic detox system at the Sierra Army Depot in California. Called the Tri-Agency Project for the three cabinet-level departments involved, the project will decontaminate a large volume of solvent-containing soil at the Depot. The SI Program coordinates the work of the three government agencies and the five contractors involved in the project. In 1994, program researchers designed a secondary optical element—the device used to focus sunlight in the reaction chamber—that dramatically improved the axial distribution of solar flux in the reactor, greatly improving the system's destruction efficiency. Continued laboratory research improved the participants' understanding of the sunlight combustion reaction, which influenced the design of the reactor vessel. The system is scheduled to begin operating at the Sierra Army Depot by the summer of 1995.

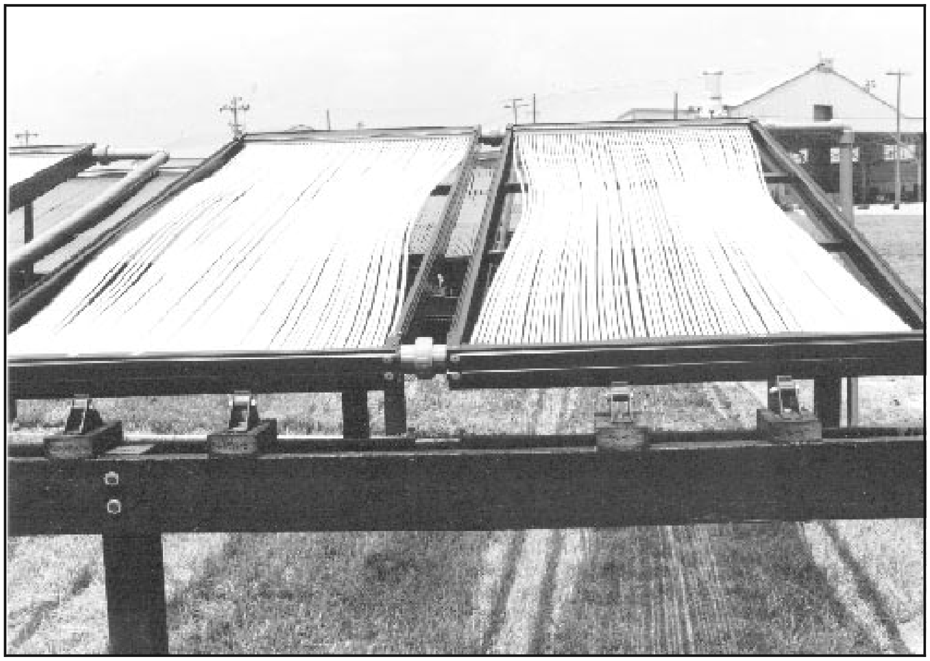
One of the keys to the eventual commercialization of PCO detoxification technologies is improving the performance of the catalyst. Faster catalysts result in smaller treatment systems, increased throughput, and reduced treatment costs. The SI Program is sponsoring the catalyst development research ongoing at Solarchem Environmental Systems. During 1994, Solarchem characterized a liquid ferrioxalate

The Challenges Ahead for Solar Detoxification

- **Consistent Performance.** The chemistry of waste treatment is highly site specific. During field tests, researchers discovered that naturally occurring compounds such as calcium carbonate and the natural background organic carbon content in the water being treated interfere with the catalyst-contaminant reaction. Researchers are addressing this problem by modifying the catalysts; they hope to be able to customize catalysts and system designs to accommodate a range of site-specific chemistry.

- **Business Barriers.** Businesses are often reluctant to use a new technology—even if it's less expensive—if a proven, widely accepted alternative is available. By collaborating with the environmental and waste management industry in the development of detox, the SI Program hopes to greatly reduce the time required for industry acceptance.

- **Handling Intermediate Species.** Depending on the reactants, hazardous intermediate compounds can be formed during the detoxification reaction. Researchers are modifying the catalysts to eliminate the production of intermediates or treat them in the detox reactor as they are produced.



Solar Kinetics, Inc., and the SI Program will use photoreactors similar to these in the demonstration project at Kelly Air Force Base. Ambient levels of sunlight are sufficient to drive the detox reaction; the reactor shown here—designed and built by American Energy Technologies and the University of Florida—is referred to as a "one-sun" design.

[$Fe_2(C_2O_4)_3$] catalyst that performs as much as 50 times faster than the titanium dioxide (TiO_2) catalyst typically used. The SI Program and Solarchem plan to test this new catalyst on fuel-contaminated groundwater at an industrial site.

SI Program researchers are also working to improve the TiO_2 catalyst. During 1994, researchers impregnated TiO_2 with various materials, such as iron, silicon dioxide, and tungsten trioxide and achieved notable improvements in its photocatalytic performance.

The Direction of Solar Detoxification in the Near Future

Thanks to the collaborations between researchers in government and industry, solar detoxification is on the way to becoming a commercial reality. The costs of building and operating detox systems are now equal to or less than the costs of comparable methods traditionally used to treat polluted air, water, and soil.

As the 1994 accomplishments discussed previously indicate, the SI Program is focusing on the field experiments to demonstrate the potential of this technology. These demonstrations will generate a considerable bank of data on operational costs and effectiveness. SI Program managers anticipate that successful demonstrations will capture the attention of the environmental remediation and waste management industry, leading to industry adoption of detoxification techniques.

During the next 2 to 3 years we will witness the further transfer of this technology from within DOE to private industry. Within this transfer phase, the onus for continued research will reside increasingly with the private sector, and the DOE and the SI Program will assume the role of technical consultants.

Solar Process Heat

American industry uses a tremendous amount of energy to heat water, create steam, and generate warm air. A variety of solar technologies are available to meet some of industry's specific heating needs, and the SI Program works to bring these technologies into wider use.

The "process" in solar process heat refers to industrial and business-scale heating loads. For example, schools, hospitals, and hotels have a great demand for hot water for cooking, cleaning, and bathing. Factories and warehouses often contain vast amounts of space that must be heated and properly ventilated. Industries use large quantities of thermal energy in their manufacturing processes. Depending on the geographic location and the specific application, solar energy can supply 30% to 70% of the heat required for these processes. In fact, several hundred solar heating systems are operating in business and government settings today, saving their users money and reducing the amount of fossil fuel we consume.

The solarwall installed on Aveda Corporation's warehouse in Blaine, Minnesota, in February was one of the SI Program's cost-shared projects in 1994. Solarwalls generate large quantities of heated ventilation air efficiently and inexpensively. The perforated solarwall is installed over a building's existing wall, creating a 4-inch gap between the two. Sunlight striking the black wall heats the air being pulled through the perforations as much as 50 degrees above the outside temperature. The heated air sandwiched between the two walls is drawn into the building's existing ventilation system. The SI Program covered 29% of the cost of the Aveda solarwall, which has a payback period of 5.2 years.

The Solar Industrial Program works with potential users of solar heating systems to determine if solar is a feasible option, given their operational needs. The program brings together potential users with solar heat companies to conduct these feasibility studies. In addition to funding these studies, the SI Program funds a portion of the solar heating systems at strategically selected sites.

Solar Process Heat in 1994

In 1994, the SI Program established formal working agreements with a variety of industrial and government organizations. These agreements, which are described in the following paragraphs, serve to develop and expand markets for solar heating technologies, reduce the perceived risks of owning and operating such systems, and expand the body of data available on how these systems perform in the field.

The SI Program entered into an ongoing collaborative program with the DOE's Federal Energy Management Program (FEMP), which helps other federal agencies reduce their energy consumption by integrating energy efficiency and renewable

The flat-plate water heating system at the Caroline Correctional Facility outside of Richmond, Virginia. Installed in 1994 as part of the SI Program's work with state governments, the system supplies 30% of the hot water for the 140-inmate facility.

energy technologies. The SI Program works with FEMP to identify opportunities for solar heating projects and is developing standard procurement procedures to simplify and expedite such projects. Through this SI Program/FEMP collaboration, three solar heating projects were initiated during the year:

- A solar water heating system for the outdoor educational center the Bureau of Reclamation will construct and lease to the Maricopa County School District in Arizona.
- A ventilation air-heating system at an aircraft maintenance hangar at Fort Carson, near Colorado Springs, Colorado.
- A solar water heating system for the Environmental Protection Agency's headquarters complex in Washington, D.C.

The SI Program continued working with state energy offices in California, Colorado, Florida, Hawaii, New Mexico, and Virginia to identify opportunities for and assist in implementing solar heating projects. These states have an interest in solar heat as an energy resource and for its environmental benefits. The SI Program encourages cooperative activities with state energy offices, jointly conducting analyses to determine where solar technology can be successfully applied. Seven new heating projects and three system rehabilitation projects were

The Challenges Ahead for Solar Process Heat

- **A Bad Reputation.** The explosive growth in the number of solar heating companies during the 1970s did more harm than good to the industry. Many early systems had operating problems that soured many potential users and others—such as financiers, insurers, and architectural engineers—on the technology. The solar heat industry that has survived and prospered into the 1990s must overcome the negative perception still lingering in the minds of many.
- **The Price of Solar Energy.** Many of the applications for solar heat are currently served by inexpensive natural gas. To overcome this hurdle, the solar heat industry must improve system efficiencies, lower costs, and reduce maintenance requirements. Solar's environmental benefits, such as negligible CO_2 emissions, offset this cost differential to a degree; such benefits are becoming increasingly important to many individuals and organizations. The Program is also targeting markets in which heating needs are met with electricity, which is considerably more expensive than gas.
- **Extended Payback Period.** The up-front costs for installing a solar heating system are high, and the payback period is often 6 to 10 years. Many potential users are unwilling or unable to incur these high initial costs even though the life-cycle cost effectiveness of solar heating systems is attractive. Third-party financing, in which a group of investors owns the solar system and sells energy to the user, is one solution to this problem.

undertaken in 1994 through state energy office/SI Program collaborations.

The SI Program is involved in a number of demand-side management projects that include businesses and electric utilities. The program works to identify promising solar heat projects for businesses within a utility district and then bring them to fruition by encouraging utility rebates to solar users, helping secure low-interest loans, and sharing the project costs. The Sacramento Municipal Utility District, the City of Tallahassee Electric Department, and the Arizona Public Service Company participated in this work during 1994, and the SI program anticipates three to five solar heating projects will be undertaken annually within each of these utility districts.

The solar collector field at the state prison in Tehachapi, California. This system heats water for the kitchen, bathing, and laundry facilities, supplying 7.2 billion Btus of thermal energy annually to the 5100-inmate prison. The system is part of the SI Program's Solar Process Heat Monitoring Project begun in 1994.

During 1994, program researchers created an automated process heat monitoring program and began collecting performance data on two solar process heat systems. The automated data base collects daily data from the large solar heating system at the California Correctional Facility in Tehachapi and the Adams County Facility outside of Denver, Colorado. Monitoring equipment in the field downloads data on the levels of solar insolation, the amount of energy delivered, and operating temperatures to a central data base in Golden, Colorado. As this data base expands to include more heating systems, solar equipment manufactures will be able to get detailed reports on how their systems perform in the field. The data base will also benefit the research community and potential solar heat users: researchers will be able to refine models of heating systems, and users will be able to acquire hard data on the reliability and effectiveness of the technology.

The Direction of Solar Process Heat in the Near Future

The accomplishments of 1994 are indicative of the direction the SI Program's solar process heat work is going.

The SI Program's work with the Federal Energy Management Program (FEMP) will expand. The federal government manages half a million buildings at 8000 locations around the world; projects with just a small percentage of these buildings represent a great opportunity to showcase solar technologies, demonstrate their reliability, and save energy and money. Likewise, the SI Program will continue to work closely with state governments, utilities, and the solar manufacturing industry.

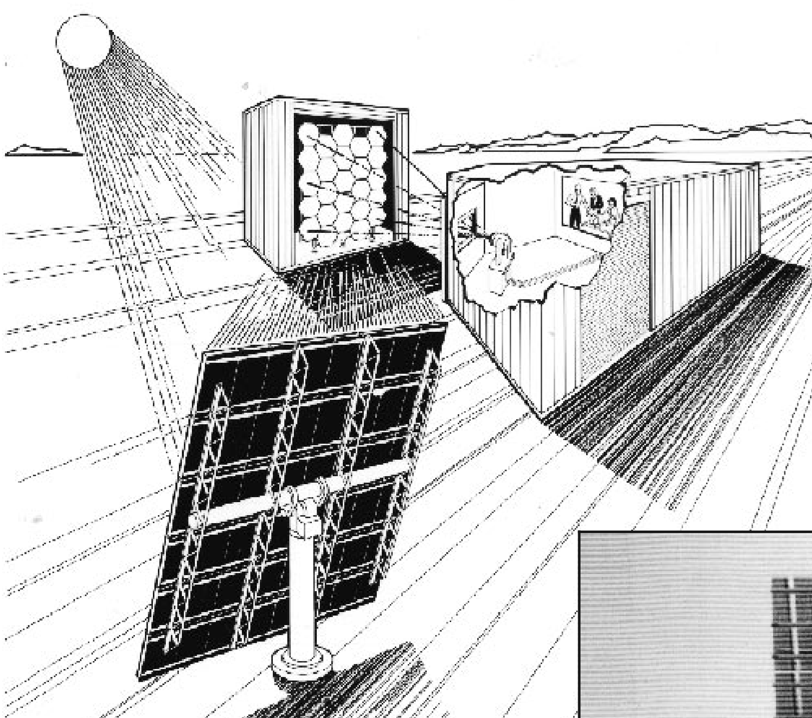
The SI Program will continue to document and promote high-profile solar process heat success stories. Solar heat is competitive and successful in niche markets today; by publicizing such successes, the SI Program generates momentum for this technology, ultimately increasing the number of industrial-scale systems in use and reducing fossil-fuel consumption.

Advanced Processes

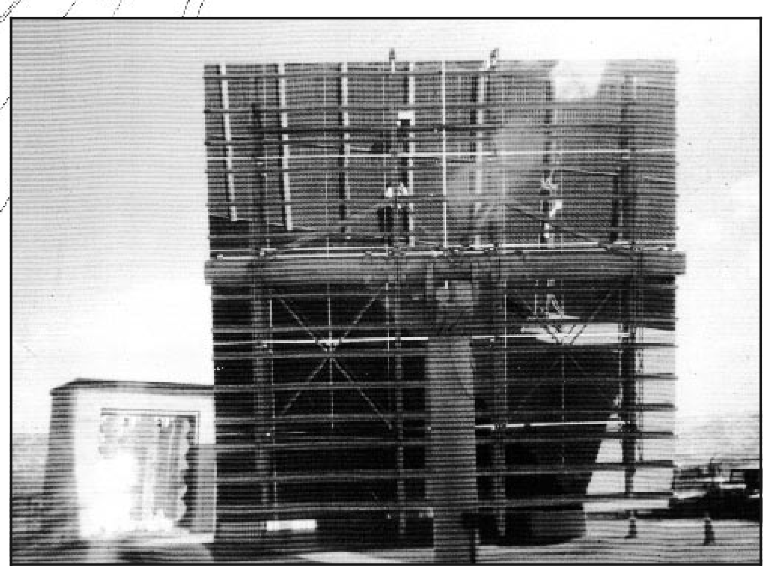
Modern industry relies increasingly on high-value, high-technology materials—such as ceramic/metal composites and surface-hardened metals—that resist wear, operate under high temperatures, and meet exacting performance specifications in harsh operating environments. Researchers in the SI Program are exploring manufacturing such materials using sunlight concentrated to laser-like intensities.

Highly concentrated sunlight—referred to as high solar flux—has properties that are well suited to manufacturing advanced materials. Researchers create high solar flux by reflecting sunlight off of precisely designed curved mirrors, similar to the way a dish antenna focuses radio waves to a point. Solar energy can be concentrated from a few hundred to 50,000 times the normal intensity of the sun at the Earth's surface. This intense energy creates and sustains extremely high—but very localized—temperatures; modest concentrations of 2500 suns can easily burn through 1/4-inch steel. Also, the surface of a material exposed to high solar flux heats rapidly, while the base or substrate remains relatively unaffected. Such rapid surface heating allows advanced surface processes such as ceramic metallization, chemical vapor deposition, and cladding to be performed using high solar flux.

Most of the SI Program work in advanced processes is undertaken at the National Renewable Energy Laboratory's High-Flux Solar Furnace in



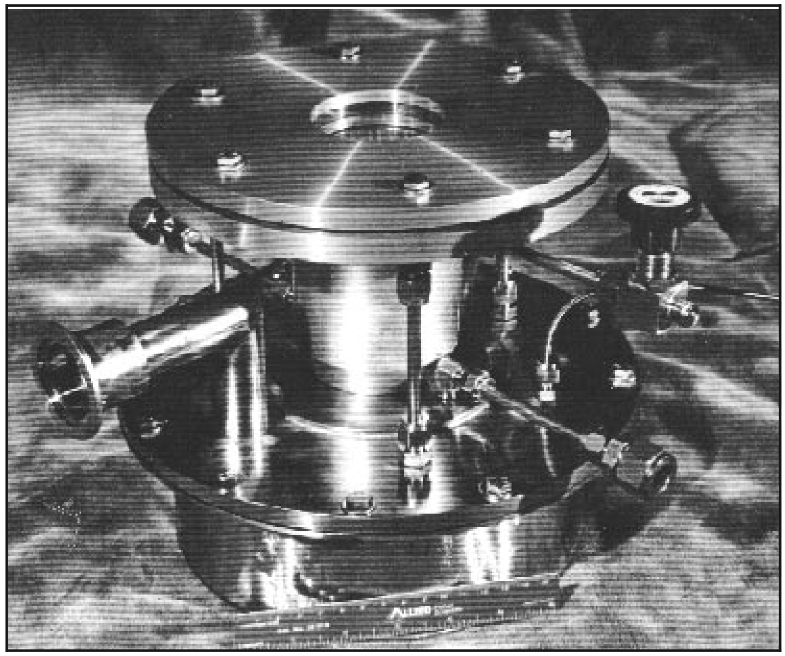
The High-Flux Solar Furnace at the National Renewable Energy Laboratory is home to the SI Program's work in advanced processes. (Above) Artist's conception. (Right) The actual facility in Golden, Colorado.



Golden, Colorado. The DOE designated the furnace a National User Facility in 1993. This designation gives qualified outside researchers easy access to this cutting-edge solar laboratory.

NREL's High-Flux Solar Furnace (HFSF) is a research tool in the vanguard of both advanced material and solar energy research. As discussed in the previous paragraphs, the HFSF offers researchers laboratory conditions unavailable elsewhere. Duplicating such laboratory conditions would be prohibitively expensive and time consuming. By taking advantage of the HFSF's user-facility status, industry can save considerably on R&D costs.

Researchers are also using the HFSF to manufacture specific advanced materials. As will be discussed in the following sections, the SI Program is working with a number of industrial partners to determine the feasibility of manufacturing various materials and components with solar flux.



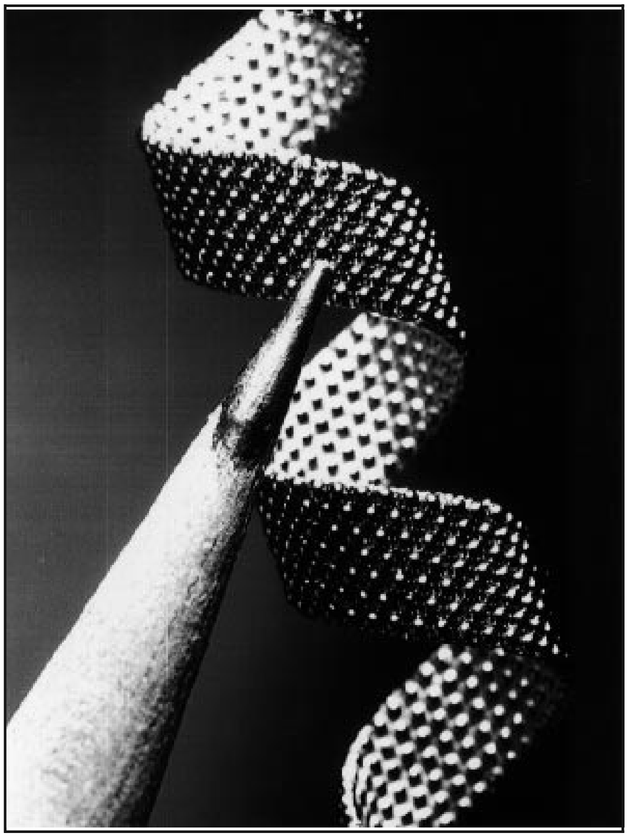
Fullerene reaction chamber. Researchers at the National Renewable Energy Laboratory used this device to synthesize fullerene molecules by bombarding a graphite pellet with solar flux. A turning mirror (not shown) mounted above the chamber directed concentrated solar flux produced by the HFSF into the aperture in the center of the top plate, shown here.

Advanced Processes in 1994

In 1994, researchers used the High-Flux Solar Furnace to synthesize fullerene molecules (C_{60}) by vaporizing graphite pellets with solar radiation. Fullerenes, a newly discovered form of carbon, have unique chemical properties that are being investigated by the research community for diverse applications such as optical devices, superconductors, polymers, pharmaceuticals, and fuels. Preliminary results indicate the SI Program's fullerene production method is

The Challenge Ahead for Advanced Processes

- **Fear of the Unknown**. Manufacturing with high solar flux is a departure from traditional manufacturing techniques, and many industries are likely to be reluctant to consider it as an energy-saving, environmentally responsible manufacturing alternative. To overcome this barrier, the SI Program will continue to seek collaborations with forward-looking industrial partners who are comfortable with the trade-offs inherent in using this technology. Solar manufacturing requires a company to be flexible with its operational schedule, as the availability of sunlight is unpredictable. Users reap the benefits, though, of rapid surface heating, sustained high temperatures, and the ability to tap energy from the entire solar spectrum, from the infrared to the ultraviolet—all of which is available from low-cost, environmentally benign solar energy.

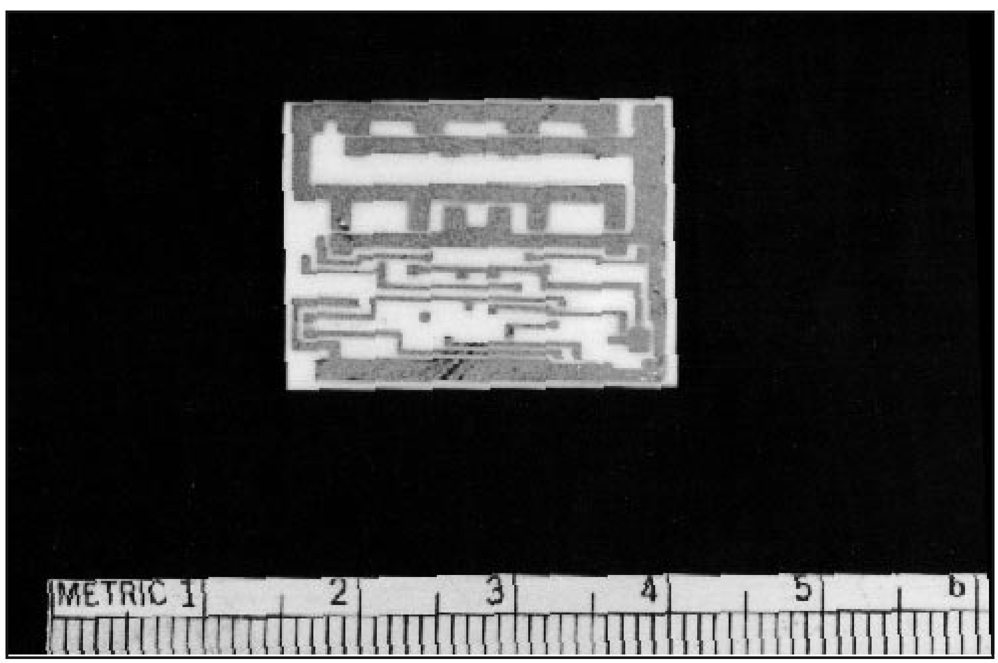


In 1994 Texas Instruments and the SI Program explored manufacturing spherical photovoltaic cells like these with solar energy.

more energy efficient and less expensive than the electric arc fabrication method typically used.

In 1994, the SI Program began working informally with Texas Instruments to investigate the feasibility of using high solar flux to help fabricate silicon photovoltaic solar cells. Researchers are using solar energy to melt silicon powders into a consolidated mass, which is then further processed into solar cells. The early experiments have been encouraging; in fact, the solar-driven melting process offers several unique advantages and minimizes subsequent processing requirements.

SI Program researchers worked with representatives from the U.S. Bureau of Mines on two research projects. The first project explored using concentrated sunlight to expand certain minerals. For example, perlite, commonly used in insulation products, is formed by exposing the raw mined material to sustained high temperatures in the neighborhood of 1000°C. Preliminary research indicates that solar furnace technology can supply the required energy, and work is ongoing to identify specific markets and potential industrial partners. The second research project investigated using solar energy to clad equipment used in mining and mineral processing. This work focuses on cladding expensive, wear-resistant metal alloys to inexpensive substrates.



A metallized ceramic circuit—consisting of a thin copper film bonded to a beryllium oxide substrate—manufactured by Brush Wellman. The SI Program and Brush Wellman are experimenting with using high solar flux to produce these electronic components.

The SI Program's 3-year CRADA with Brush Wellman, a leading electronics/ceramics manufacturer, continued in 1994. Under the CRADA, the two partners are determining the feasibility of using high solar flux to bond ultra-thin layers of metal, such as copper, palladium, platinum, or gold to ceramic substrates. Experiments have shown that the resulting metallized ceramic components are higher in quality than those manufactured using traditional processes. These electronic components are playing an increasingly important role in America's automotive, computer, and telecommunications industry.

The Direction of Advanced Materials Manufacturing in the Near Future

The SI Program will continue to seek high-level industrial collaborations similar to the partnerships mentioned previously with Brush Wellman and Texas Instruments. Applied research projects on this scale offset industry's R&D costs and advance the fundamental understanding of concentrated sunlight and its industrial applications.

The program will also evaluate new ideas as part of its applied research investigations. In addition to continuing fullerene research, the SI Program will investigate using solar flux for mineral processing, pumping lasers with solar energy, and initiating self-propagating exothermal chemical reactions for forming high-technology materials.

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